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Structure Visualization for a Gas-Liquid Flow

Quantitative Flow Structure Fields

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Abstract : When considering the flow of a two-phase mixture, the complete characterization of its behavior requires not only the evaluation of its temperature and pressure evolutions, but also the description of the distribution of the phases (the so-called "flow structure"). This is of great importance in problems concerning the analysis of the solicitations undergone by the containing ducts, both from a mechanical point of view and - even more important - when heat transfer at fixed power is involved. In the present paper some methodologies are presented, which proved to be very useful in the description and quantitative visualization of the structure of a two-phase flow: for liquid-gas mixtures, they are based on relatively simple experimental acquisitions of a single quantity and allow a detailed visualization of the flow structure without requiring visual observation of the same.

Keywords : Visualization, Two-phase flow, Section fields, Void fraction, Flow complexity.

1. Introduction

Two-phase flows of liquid-liquid and liquid-gas mixtures are very common in a broad range of chemical and industrial plants. It is therefore evident the importance of a deep understanding of two-phase flows for a good design in all these fields. As rigorously derived constitutive equations have not been formalized up to now to complete the theoretical description of the flow, experimental investigations are fundamental, first of all to describe "what happens" in the flow, which is the first step towards a comprehension of the phenomenon. In particular, though the macroscopic structure of two-phase flows is widely described in literature in section- and/or chord-averaged terms, the local flow structure was on the contrary very little investigated, despite its importance as a beginning for developing physically-based models, as a fundamental aspect in problems involving duct solicitations and fixed-power heat transfer (first of all to avoid burnout risks), and - more recently - as an input to CFD simulations. From a certain point of view, the best description of the flow structure can probably be obtained by means of short exposure time photographs or - better - high speed cinematography. As an example, in Fig. 1 some examples of short exposure time pictures of air-water flows are presented. These techniques constitutes an enhancement with respect to visual observation of the flow, both because the camera is able to "see" much faster than the human eye and because there is a registration of what happens; but such an analysis has also three main problems: the first is that it is very difficult to extract quantitative information from the acquired material - image processing is in general quite complex, in particular when the imaged media are both transparent as for example air and water or water and water vapor. The second is that it is an almost two-dimensional representation. Only by means of very sophisticated and expensive tomographic imaging techniques it is possible to capture a three-dimensional description of the flow, which in some cases may not show a very high resolution. The third and last is that such an investigation requires a duct with transparent walls, which is not the case of structural materials for industrial pipes. A different kind of analysis would thus prove very useful, and this is the scope of this work: to give a local time-averaged description of the flow structure with the advantage to be three-dimensional and quantitative, requiring only relatively simple experimental acquisitions (even without transparent ducts) and data processing, and helpful for physical and mathematical models.

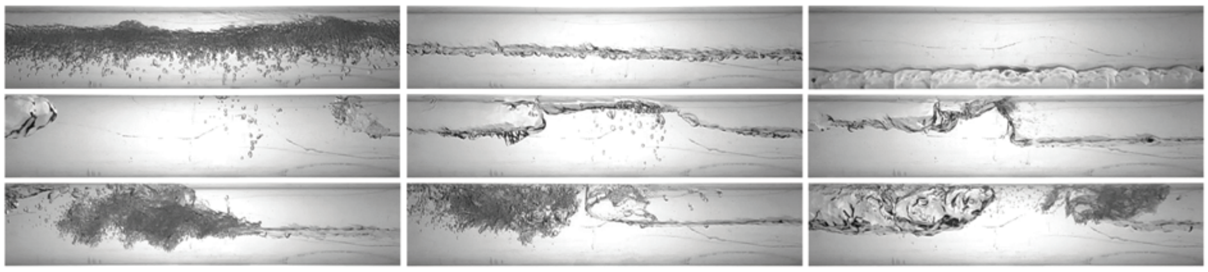

Fig. 1. Examples of short exposure time (1/8000 s) pictures of air-water flows in a circular duct with uniform diameter (60 mm i.d.). Flow direction is from left to right; a white semi-transparent panel was placed between the duct and the two illuminating lamps (one behind and one below the duct).

2. Quantities Used for the Description of the Flow Structure

The flow of a two-phase mixture can be completely characterized by means of six quantities: temperature, pressure, phases velocities and two other quantities able to describe the structure of the flow. The last ones are the object of this study. When considering a two-phase flow structure, in most case the local "void fraction" α_P only is taken into consideration. It is a local, time-averaged quantity which can be defined as the probability for a point inside the flow to be immersed in the gaseous phase (Delhaye, 1968). It can be calculated as the mean of the phase density function df($\mathbf{p}$,t), a quantity which can be defined as follows:

df($\mathbf{p}$,t)	=	1	if at instant t point $\mathbf{p}$ is immersed in the gaseous phase
	=	0	if at instant t point $\mathbf{p}$ is immersed in the liquid phase

and consequently $\alpha_P = \int_T df(\mathbf{p},t)\, dt \,/\, T$. In practical terms, the phase density function is sampled by means of suitable probes, and therefore the local void fraction is calculated in discrete terms:

$\alpha_P = \sum_{i=1,N} df(\mathbf{p},i) \,/\, N$ if T is the sampling interval and N is the number of samples acquired during the same.

Yet the local void fraction α_P alone is not enough for an exhaustive description of the structure of the flow. For example, $\alpha_P = 0.5$ only tells that point $\mathbf{p}$ was immersed in the gaseous phase for one half of the investigation time - but it cannot be inferred if a single long plug (see for example the first image on the left of the second line of Fig. 1) or a lot of small bubbles passed through that point. Nevertheless, this second piece of information is indeed enclosed in the phase density function. To "extract" it, we found it useful to define another simple quantity, which were able to discriminate among situations similar to the ones of the proposed example. We named it "local flow complexity" cf_P, because it meters how much "complex", rich in changes between the phases, the flow structure is.

$cf_P(\mathbf{p},t,T)$ = (number of 0-1 or 1-0 transitions in the phase density function sampled in point **p** during the sampling interval from t to t+T) / (maximum number of potential transitions in the same phase density function signal) = $N_T / (N - 1)$

As α_P, cf_P it is a time-averaged local quantity. Possible values for this quantity are all the rational numbers between 0 and 1, both included: 0 means no transitions in the sampled phase density function, i.e., single-phase flow through point **p**; 1 means a transition between each pair of consecutive values of the sampled phase density function, i.e., the most complex detectable flow, with a great deal of very short and/or fast structures. Upper complexities are possible, but they cannot be revealed due to the limits of the acquisition chain (see section 3). In general terms, along with the above given definition the flow complexity is not able to tell if the number of interfaces seen by the probe is due to the dimensions of the flow structures or to their velocity. To discriminate between the spatial and the cinematic aspects, another quantity called "spatial flow complexity" scf_P can be defined:

$$scf_P(\mathbf{p},t,T) = cf_P(\mathbf{p},t,T)\; w_S \,/\, w(\mathbf{p},t,T)$$

where $w(\mathbf{p},t,T)$ is the mean flow velocity in point **p** during the sampling interval from t to t+T, and w_S is a "reference" flow velocity (the most natural choice for its value is 1 m/s). $w(\mathbf{p},t,T)$ can be calculated by cross-correlation techniques applied to proper couples of phase density signals, or it can be estimated in section-averaged terms through the volumic flow rates and the void fraction. In the present paper, two-phase flow structure will be described and visualized mostly by means of α_P and cf_P, in union with a third quantity which can be easily calculated from them: the local mean temporal length of the gaseous phase structures τ_{aP}, defined as:

$$\tau_{aP} = \alpha_P\, N \,/\, \{\, f\, [\, cf_P\, (N-1)/2 + 1\,]\, \}$$ where f is the sampling frequency of the probes.

As α_P N gives the number of samples in which the probe detected gaseous structures and $cf_P(N+1)/2$ ($\pm$ 1) is the number of flow structures seen by the probe, $\alpha_P N/[cf_P (N-1)/2 \pm 1]$ would give the local mean length of the gaseous phase structures in terms of samples; dividing it by the sampling frequency in Hertz we obtain the corresponding quantity in seconds. If $cf_P = 0$, τ_{aP} is equal to 0 too if $\alpha_P = 0$ (no gaseous phase structures seen by the probe) and is otherwise equal to the sampling interval length if $\alpha_P = 1$ (only gaseous phase seen by the probe). For further information about α_P, cf_P and scf_P see (Guilizzoni, 2002, Arosio and Guilizzoni, 2003). For all the three quantities, it is possible to draw 2D and 3D graphs on the duct section (in cylindrical or Cartesian coordinates), thus creating surfaces able to visualize the distribution of each quantity in the different sections of interest. By this way, the synergic use of α_P and cf_P allows a detailed description of the structure of a two-phase flow. As it will be shown in section 5, due to the pseudo-periodicity of the phenomenon and to the possibility to commute spatial and time averaging for the introduced quantities, such a description is equivalent to a time-averaging of 3D tomographic images of the flow. Therefore one can easily visualize the flow, almost as he was directly observing it. Moreover, the calculated values and the constructed fields on successive sections along the axial development of the duct itself, or on the same sections when varying the flow regimes, enable the visualization and quantification (by means of point-to-point differences between the fields themselves) of the evolutions of the flow. As a derived quantity, τ_{aP} gives in effect no further information than the couple α_P - cf_P, but it appears to convey visual information in a most efficient way, so section distributions of τ_{aP} will be presented too.

3. Experimental Set-Up and Procedures for the Creation of Section Fields of the Local Quantities

The experimental acquisitions were taken on the plant available in the Thermo-fluid dynamics Laboratory of the Department of Energy of the Politecnico of Milan, which consists in two loops: a closed loop for the liquid phase (water) and an open loop for the gaseous phase (air), which share a portion where the two-phase flow sets up. This test section is approximately 12 m long and it is made of Plexiglas®, to allow visual and photographic observation of the flow. For details about the plant configuration see (Arosio and Guilizzoni, 2003). On the test section, a series of optical probes are placed, to sample the phase density function in each point of interest, along with the scheme presented hereafter. The operating principle of an optical probe is the following: a light source generates pulses (2000 times per second) which run inside an optical fiber, whose point – inserted in the flow – is conically tapered (from 200 μm to 40 μm). When the tip of the probe is immersed in water, the pulse leaves the fiber and is lost; otherwise it is reflected back, modified only in phase, along the glass fiber and a photodiode registers it, emitting a voltage signal which is then amplified and converted into a binary signal. Theoretically, this kind of probe is able to sample the true phase density function. In practice there are some limits, both spatial (interference between the probe and the smallest flow structures) and temporal (sampling frequency insufficient to capture the smallest flow structures, aliasing). For a detailed analysis of these effects see (Barrau et al., 1999). From a practical point of view, our previous trails did not evidence a significant influence of the cited limits on the calculated local void fraction and flow complexity. In order to create a section distribution of a local quantity, the first thing is to get a valid mesh of experimental points. After a great number of tests, the scheme represented in Fig. 2 were selected: the positioning of experimental points on each duct section of interest was fixed uniformly spacing them along 9 directions with an inclination from the vertical axis going from -80° to 80°, 19 points for each direction.

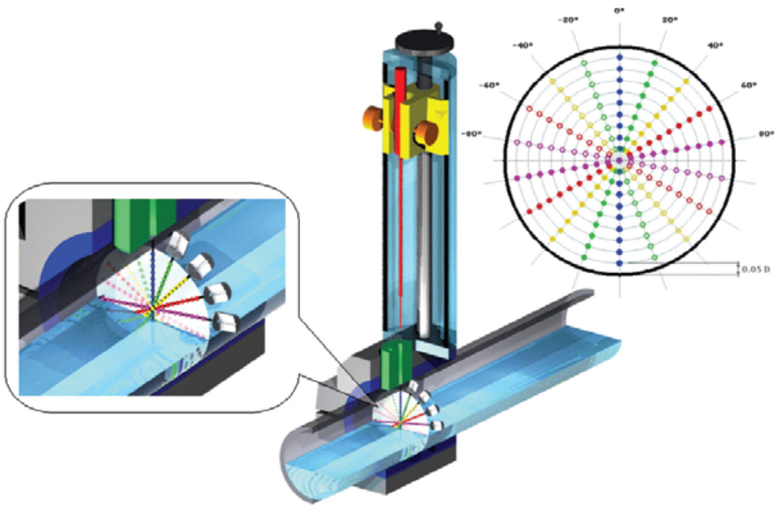

Fig. 2. Positioning of the experimental points on the duct section and scheme of the probe support.

For mixtures flowing in ducts with uniform diameter or with singularities which preserve the axial symmetry of the flow (for example axisymmetric expansions or contractions of sections), the inclinations were reduced to 5, as it is sufficient to construct one half of the field and the other can be obtained by mirroring. The “sinking” of the probe within the duct along each direction is made possible by the micrometric screw present on the probe support, while the choice of the direction is made turning the duct itself, on which the probe support is fixed. The significance and precision of the calculated distributions depend obviously on the number and position of the points where the phase density function is sampled and on the repeatability of the sampling. Our tests (150 repeated points) evidenced for α_P an AAD% = 2.12 with a std.dev. of the absolute % error equal to 1.21). They also depend on the method chosen to construct the field from these experimental points, i.e., on the algorithm used to interpolate the value of the local quantities in all the points belonging to the duct section but not directly investigated experimentally. Four three-dimensional interpolation methods were tested and compared: linear interpolation, cubic spline interpolation, Bézier approximation and approximation by means of an exponential spline. The last method tested is a spline based on an exponential smoothing of the values of the quantity in the base points. For a detailed description of the four methods and of how section distributions look like when calculated with each interpolation algorithm see (Foley et al., 1996; Guilizzoni, 2002). After an extensive test campaign, cubic interpolation seemed to be the best choice: on one side, as experimental uncertainty is little and the evolutions of the quantities can be very fast, interpolating techniques are better than approximating ones. On the other side, as the investigated quantities are characterized by a smooth behaviour, cubic interpolation proves to be more suitable than linear interpolation.

4. Examples of Visualization

In Figs. 3 and 4 some examples of visualization of section distributions of α_P, cf_P and τ_{aP} are proposed, drawn with different representation techniques.

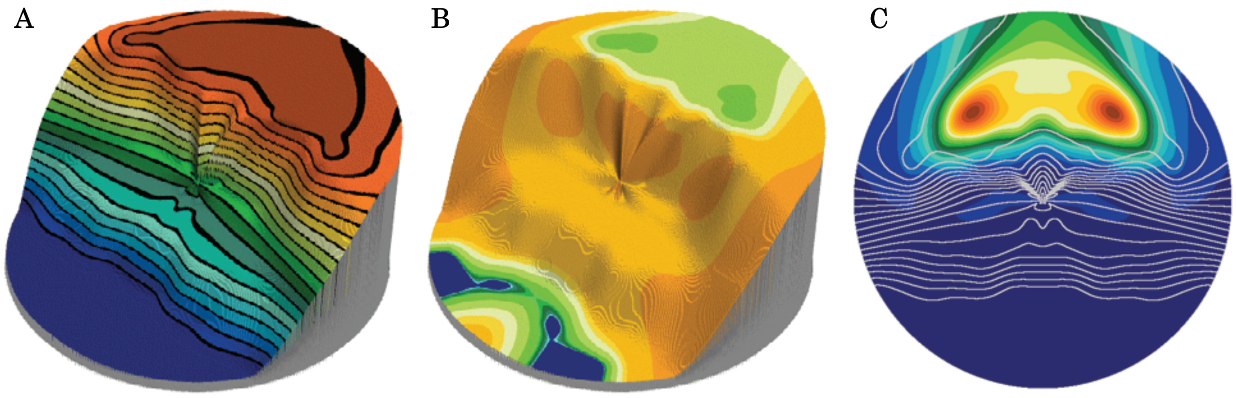

Fig. 3. Examples of visualizations of section distributions for the flow described in the second example of section 5 (Fig. 6); A) 3D view of α_P section fields: values from 0 (blue) to 1 (brown), black iso-α_P lines spaced by 0.05; when the iso-α_P lines enlarge it means that in those regions the differences in α_P are less than 0.01; B) 3D combined view of α_P and cf_P section fields: the height of the plot is proportional to α_P, the color is related to cf_P (non-uniformly spaced color scale from 0 to 0.043); C) 2D combined view of α_P and τ_{aP} section fields: light gray iso-α_P lines are traced over a plot in which the color is proportional to τ_{aP}, visualized with a uniformly spaced color scale going from 0 (blue) to 0.5 s (brown).

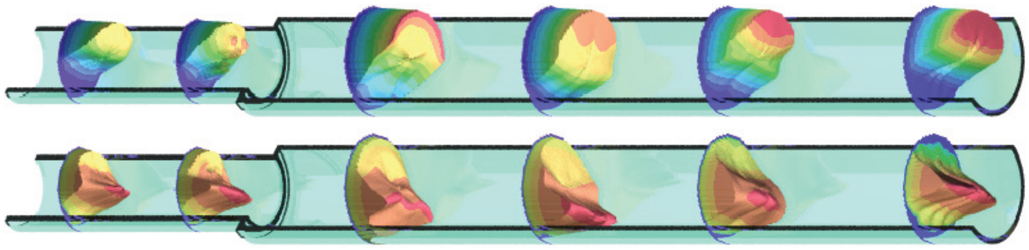

Fig. 4. Evolution of α_P (top) and cf_P (bottom) section fields along a duct with a sudden section expansion (60 i.d. to 80 mm i.d.) for a flow with liquid mass flow rate Gl = 7.0 kg/s and gas volumic fraction xv = 0.66. Non-dimensional axial positions of the investigated sections: z/D = -28.3, -1.2, 1.8, 9.0, 25.9, 50.0.

5. Comparison between the Information Obtainable from Local Quantities Section Fields and the Visual Observation of the Flow

Three examples of comparison between the information obtainable from α_P, cf_P and τ_{aP} section distributions and photographic images of the flow will be described in the following. The pictures were taken with an exposure time of 1/2000 s and offer an almost "instantaneous" shot of the flow. As all the presented flows are axisymmetric, each section field will be represented on one half section only.

EXAMPLE 1 – Plug Flow in a Duct with Uniform Diameter

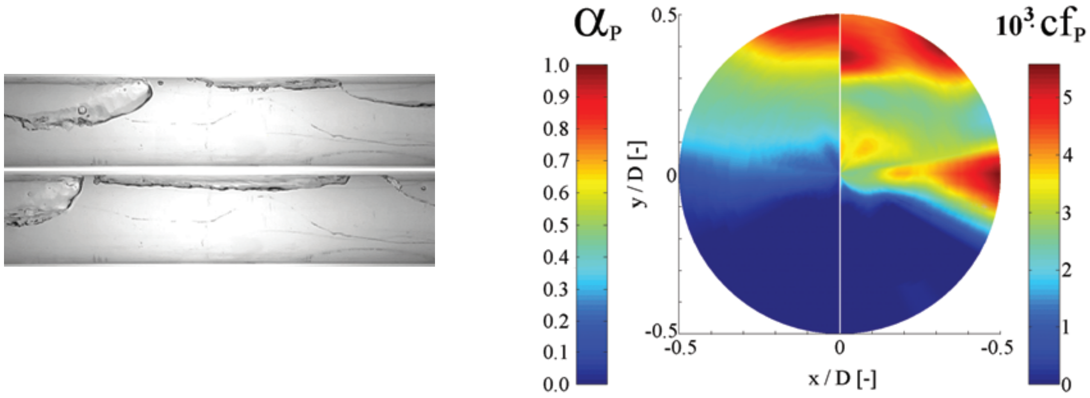

Fig. 5. α_P and cf_P section distributions compared with photographic shots of the flow (exposure time 1/2000 s) for a flow with liquid mass flow rate Gl = 3.0 kg/s and gas volumic fraction xv = 0.26, in a uniform diameter (60 mm) duct. Non-dimensional axial position of the investigated section: 74.7 from the air-water mixing section.

The local void fraction field is depicted on the left part of the chart. It is a good example of distribution with values almost uniformly increasing when moving upwardly on the vertical axis of the section; but the gradient of α_P shows a rapid increment close to the top region of the distribution. This behavior reflects perfectly what can be observed looking at the picture of the flow, which shows that it is a "classic" plug flow, with a lower single-phase (liquid) region surmounted by another where liquid plugs and airpockets alternate. Moving towards the top of the duct section, plugs are shorter and this causes the progressive increasing of α_P in that region; in some cases, plugs do not touch the duct top wall, which remains insulated by an air "cushion", and the distribution exhibits the characteristic sudden rise. The cf_P section field (right half of the chart) memorizes extremely low values, coherently with the presence of plug flow, with sharp interfaces among the macro-structures of the flow.

EXAMPLE 2 – "Wings" after a Sudden Section Expansion

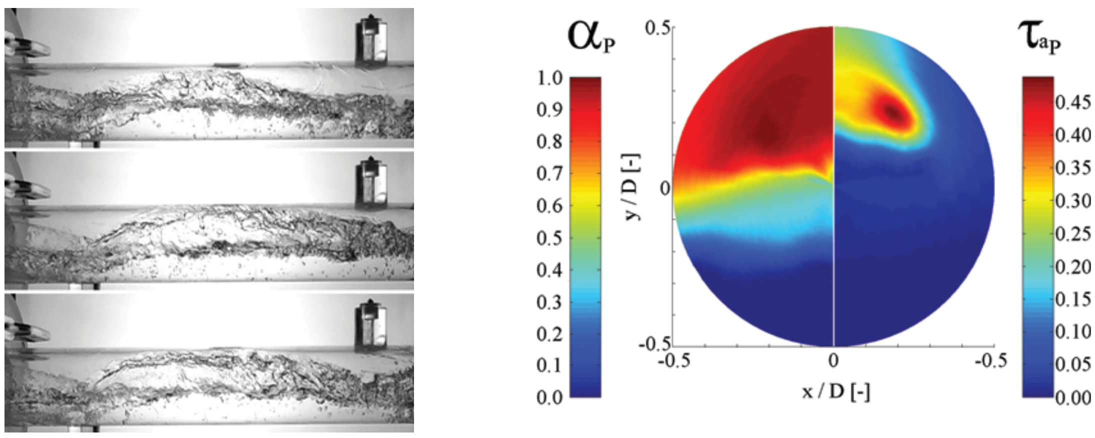

Fig. 6. α_p and τ_{aP} section distributions compared with photographic shots of the flow (exposure time 1/2000 s) for a flow with liquid mass flow rate Gl = 4.5 kg/s and gas volumic fraction xv = 0.26, 1.8 diameters after a sudden expansion in the duct section (60 i.d. to 80 mm i.d., 2827 mm^2 to 5027 mm^2).

When a slug flow with relatively low superficial velocities of the phases encounters a sudden expansion in the duct section, a large modification in its structure occurs, showing a local α_P section field which in its upper-central part presents a region with very high α_P (superior to 0.95), surrounded by two “wings” with a lower α_P. This is due to the bouncing of the liquid phase on the bottom of the larger duct after the singularity, which creates two liquid “wings” around a gaseous core. This behavior is recorded also in the mean temporal gaseous phase length τ_{aP} section distribution (right half of the graph), in which a central region with high τ_{aP} (low cf_P) is present, surrounded by two wings where τ_{aP} is a magnitude order lower (while the gaseous core is permanent, the “wings” are intermittent, because there is plug flow before the singularity). Some "wings" collapse towards the center of the duct, decreasing α_P and τ_{aP} values in the upper central part of the graph. Even if it is not sufficient by itself to completely describe the flow, the τ_{aP} section field proves to be useful in giving an immediate idea of the structure of the flow.

EXAMPLE 3 – "Intermittent Jet" after a Sudden Section Expansion

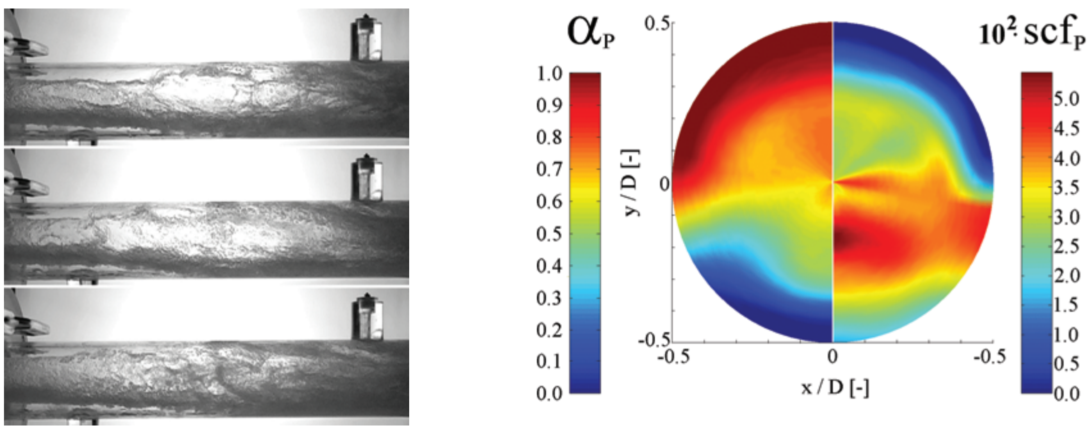

Fig. 7. α_P and scf_P (w_S = 1 m/s, w estimated in section-averaged terms using homogeneous model) section distributions compared with photographic shots of the flow (exposure time 1/2000 s) for a flow with liquid mass flow rate Gl = 7.0 kg/s and gas volumic fraction xv = 0.48, 1.8 diameters after a sudden expansion in the duct section (60 i.d. to 80 mm i.d., 2827 mm^2 to 5027 mm^2).

Looking at the α_P half-section field in Fig. 7 (left side of the graph) a behavior opposite to the one of the previous example is observed: in the half-moon top region of the distribution α_P is very high, then the values decrease towards the center of the duct section. The comparison with the corresponding shot of the flow shows that this is the “signature” of the "intermittent jet" a slug flow with high superficial velocities creates when it enters the larger duct downstream the singularity. In the scf_P section distribution there is a top, half-moon low-scf_P region too, which is less extended (apart from the different color scale) because this more sensitive quantity is able to detect the instabilities of the "jet" walls. An analogous behavior can be observed in the lower region of the field. It appears less sharp because of the presence of a component of back-flow generated by the impact of the "jet" against the bottom of the duct.

6. Conclusion and Prospects

The synergic use of three quantities - the void fraction, the flow complexity and the mean temporal gaseous phase length - has been proposed to characterize the local structure of a two-phase flow. Together, these quantities allow a description (in time-averaged terms) almost equivalent to the one obtainable from a visual or photographic observation of the flow, with the advantage of being quantitative, three-dimensional and usable also on non-transparent ducts. Various examples of equivalence between the section distribution of these quantities and photographic images of two-phase flows have been given, and a series of flow structure representation techniques were presented. In a following paper, an extended series of results concerning the evolutions of two-phase flows in ducts of uniform diameter and in particular for ducts which present section singularities will be presented.

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